

A STRATEGY FOR ASSESSING THE VOLATILES FOR THE LUNAR OUTPOST. J. B. Plescia¹, P. D. Spudis¹, B. Bussey¹, R. Elphic², S. Nozette³, Andy Phipps⁴. ¹Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723. ²Los Alamos National Laboratory, MS D466, Los Alamos, NM 87545. ³ACT Inc. Chevy Chase, MD. ⁴Surrey Satellite Technologies, Guildford, United Kingdom.

Introduction: The Vision for Space Exploration (VSE) calls for the permanent occupation of the Moon using robots and humans. A key objective of the VSE is to the understanding and exploitation of lunar resources in support of the human exploration. To achieve the objective of sustained lunar occupation, local resources must be exploited to the greatest possible extent and thus reduce the direct reliance on materiel from Earth. An important programmatic constraint on the VSE is the philosophy of “*pay-as-you-go*.”

To facilitate *pay-as-you-go*, prevent expenditures on technical blind alleys, and reduce programmatic and technical risk, one needs to “*know before you go*.” Key decisions with respect to resource utilization include the choice resource, its use, and production method. Using ISRU is a necessity to fulfill the objectives of the VSE as articulated by the President and within the context of *pay-as-you-go*.

While it is possible now, using our current understanding of maria and highland chemistries, to make a decision regarding which “ore” to exploit, such a decision in the absence of an understanding of the global resource potential of the Moon, particularly the pole, could be fiscally and programmatically unsound as well as impact the schedule of outpost development. The key unknown at present is volatile potential of the lunar polar regions.

ISRU Requirements: Hydrogen and oxygen are the most valuable elemental resources and can be found anywhere on the Moon. H₂ typically occurs in very low abundance (~50 ppm) whereas O₂ makes up ~45% of the regolith by mass. The issue of mining H and O is not so much where to go as what is involved in obtaining those elements in different places using different feedstocks.

The Known Moon: The Apollo and Luna missions provided a database sufficient for understanding the chemical and physical properties of the equatorial lunar regolith. Several processes have already been identified to extract O₂ from the both mare and highlands regolith; each having different energy requirements, production efficiencies, and infrastructure. Most processes are inefficient (less than a few percent yield) and require significant amounts of energy (10’s KWh/kg); some are feedstock-sensitive (e.g., ilmenite reduction requires high-Ti mare regolith).

The Unknown Moon: The lunar poles are both different and largely unknown compared with the

front-side low latitude area. Although the bulk composition is expected to be highlands and the general regolith properties similar to elsewhere, the permanently shadowed regions *may* hold significant water ice (and other volatiles) mixed with the regolith. While enhanced levels of hydrogen are certainly present, we do not know the form (H₂ or H₂O) or the physical properties of the deposit. If present as H₂O, that water can be electrolyzed to produce both H₂ and O₂ at relatively low energy expenditure.

While the Lunar Prospector neutron data indicate enhanced H in the polar areas, those data have insufficient resolution to differentiate between regional enhancement at 100-150 ppm and local concentrations in shadowed areas possibly in excess of 1000 ppm. This distinction has important implications for harvesting the hydrogen. If it is uniformly distributed, it is probably largely of solar wind origin and could be extracted anywhere in the polar area. If it is sequester in permanently shadowed areas, then it the challenges of harvesting the hydrogen would be much different.

Implementation Approaches: To determine which model is correct, surface exploration must be conducted and *in situ* analyses made. Studies conducted during Robotic Lunar Exploration Program (RLEP) and Lunar Precursor Robotic Program (LPRP) considered mission options to explore the illuminated and permanently shadowed polar regions. Options considered include a rover/lander combination landed in an illuminated region; the rover was then deployed to explore the illuminated and shadowed regions. In other options, a stationary lander was deployed in an illuminated region and a second vehicle, carrying the rover, was landed in the shadowed area; once landed, the rover proceeded on its own and the lander ceased functioning. For the mission scenarios involving two landed vehicles; single and dual launches were considered. Because of their capabilities, these missions had the ability to definitively determine the hydrogen form, distribution and concentration in both the illuminated and shadowed regions as well as conduct a complete retinue of environmental assessments.

An alternative architecture involving more focused set of experiments for assessing the hydrogen content has also been considered. This involves the use of hard landers to deploy a highly-focused payload, in this case to assess the hydrogen content of the regolith. The methodology is similar to that envisioned for de-

ployment of a hard-landing seismometer (“Tonto”) from the Ranger spacecraft as it approached the Moon.

A small package (e.g., a sphere) would be deployed from orbit. A retrorocket would be used to null out the orbital and most of the descent velocity. The package designed to withstand the shock would impact the surface and operate for a few hours. The payload could include: a neutron spectrometer, volatile analysis package, and an elemental analysis experiment (e.g., XRF, apx). Unlike the Japanese Lunar A mission, the package would remain on the surface rather than penetrating into the subsurface. Multiple packages would need to be deployed to obtain coverage in both the illuminated and shadowed areas.

Assessments using small landed packages would provide some data, but would be unable to address the broad distribution and concentration of the hydrogen. A mobile platform with the ability to collect and analyze subsurface samples will still be required. But, the understanding gained from these hard landed packages would provide very explicit guidance for a more sophisticated future mission having mobility.

Energy / Technology Issues: The energy needed to produce O_2 and H_2 is a more complicated than a simple comparison of the energy required to break the Si-O / metal-O or H-O bonds. The total cost includes the energy to extract the ore; to emplace the infrastructure, and the energy to break the molecular bonds. Previous ISRU studies have noted that the presence of polar water and other volatiles must be answered before an accurate ISRU cost/benefit analysis can be completed. Finding such high-grade deposits allows “bootstrapping” of capability from robotic-scale infrastructure and provides high leverage on resource production early in the program. Water electrolysis is a mature technology, used extensively at industrial scales (e.g., submarines). Extracting oxygen from silicates has been done at large scales only in the aluminum industry; it is a very energy-intensive.

Consequences: Once the presence, form, distribution and concentration of polar ice are determined, an informed decision can be made as to which ore (mare or highlands regolith or polar ice) is the most relevant to the lunar outpost architecture. Cost savings and risk reduction might come from more than simply lower energy requirements; it may be possible to extract polar volatiles *in situ* without moving the regolith. But, that possibility is a function of the nature of the deposit and distances involved, which are unknown at present.

It is true that the poles are more benign from both power generation and thermal loading perspectives. There are locations near the poles of near-permanent sunlight and a near-continuous temperature of $-50^\circ \pm$

$10^\circ C$, compared with the two weeks of darkness and $250^\circ C$ temperature excursions at lower latitudes.

Subsequent missions could demonstrate regolith mining, conduct extraction demonstrations, and experiment with conversion and storage techniques and processes. These would allow an understanding of the advantages and problems of each method and allow informed decisions as to which technique to pursue.

Conclusions: We could choose to go to the equator today; we have sufficient knowledge of the materials to design a human outpost. We have enough samples and surface information to design and implement an ISRU plan; we know the level of difficulty and the likely costs of producing a given amount of product per unit time. If such a choice is made, there is no need for *any* early, information-gathering robotic missions, including the Lunar Reconnaissance Orbiter. However, we believe it is unwise to choose a specific site and process prior to characterizing the polar volatiles. The unique nature of the polar resources could significantly reduce costs and enhance both the speed and scope of capabilities. Over the next six years (2006-2012), NASA will spend $\sim \$100B$. An early, premature decision (*go before you know*) may avoid of near-term expenditures, but could result in higher risk and possibly a much higher overall cost. An robotic program of 1-2% of the total program cost is not unreasonable, considering that permanent, sustained human presence on the Moon is a prime objective.

Table 1. Energies required for selected lunar resource processes	
Operation	Specific Energy
Equatorial Moon	
Excavation of regolith	0.01 kWh/kg regolith (electric)
Oxygen from reduction of SiO_2 to $Si + O_2$	10.4 kWh/kg (electric)
Hydrogen extraction of from dry regolith ¹	2250 kWh/kg (thermal)
Energy to extract 1 kg of H_2 from equatorial Moon	2250 kWh/kg
Polar regions	
Excavation of regolith	0.01 kWh/kg regolith (electric)
Extraction of water from icy regolith ²	2.8 kWh/kg H_2O (thermal)
Oxygen from electrolysis of water	4.7 kWh/kg (electric)
Hydrogen from electrolysis of water	48 kWh/kg (electric)
Energy to extract 1 kg of H_2 from poles of Moon	51 kWh/kg
1. Assumes 100 ppm H_2 , heated to $800^\circ C$.	
2. Assumes 1% ice, heated to $100^\circ C$.	